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Is the Cerebellum Involved in Motor and Perceptual Timing: A Case Study (1)

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Preface

This study is a preliminary report on the role of the cerebellum in timing. It is preliminary because certain problems with the data of the patient to be described prevent as firm conclusions as we would like. As a result the study needs to be extended to other patients of similar type. This interim report serves to illustrate the issues we are investigating, the methods we employ, and tentative conclusions and speculations about the role of the cerebellum in timing.

Introduction

Many motor activities, such as playing a musical instrument, require precise timing. The rate of such timed activity can be fast or slow, and the rate can be modulated in various ways. A goal of our broader research program has been to understand the nature of the brain's timing system. One question concerns whether timed production with one muscular system is related to timing with another. In one study (Keele, Pokorny, Corcos, and Ivry, 1985) we found that people who are regular in timing with one effector, the finger, also tend to be regular in timing with another effector, the foot. Such a result suggests that at least some portion of timing is in common to diverse muscular systems. Moreover, in the same studies we found that people who are relatively precise in motor timing also tend to be better judges of the differences in durations intervening between brief auditory events. Such an outcome is consistent with the possibility of a common timing mechanism between perception and production.

If there is a timing mechanism shared by perception and production, then perhaps simultaneous demands on the mechanism by concurrent perception and production would produce interference. Pokorny (1985) has found such interference between timing finger movements and judging the duration of tones. Related evidence has been found by Meyer and Gordon (1985) and Gordon and Meyer (1984) for speech productions and perceptions in which timing is crucial. Thus, individual difference studies and time-sharing studies suggest a timing mechanism in the brain common to different muscles and perhaps even shared by perception as well.

A third approach to the study of timing, and the one used in the current study, is to examine brain structures that might underlie timing by examining neurological patients. We report here on a patient with a unilateral lesion in the cerebellum. The advantage of such a patient is that, given the dominance of ipsilateral connections between cerebellar hemisphere and limb, we could use performance of one hand as a

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control for the analysis of the other. This reduces the necessity for obtaining well matched control subjects.

It has often been suggested that the cerebellum is involved in timing of motor activity (c.f., a review by Brooks and Thach, 1981). For example, Hallet and Khosbin (1980) examined electromyographic patterns from the biceps and triceps in back and forth forearm movements and found departures in cerebellar patients from the typical alternating bursts of agonist and antagonist muscles of normal people. For cerebellar patients the bursts were more variable in duration, and agonist and antagonist bursts overlapped in a highly variable way. Likewise, Conrad and Brooks (1974) found that cooling of the dentate nucleus, a substructure of the cerebellum, affected the timing of arm movements of monkeys, making them both longer and more variable in duration.

It appears that the cerebellum affects timing, but there are two potentially different mechanisms for such an effect, and those mechanisms previously have not been differentiated. One possibility is that the cerebellum is part of a timing mechanism, which we will call a clock, that is responsible for timing the interval between successive movements. Increased timing variability due to cerebellar damage could be due to damage to part of the clock itself. Once a clock signals the time for a movement to begin, various presumed neural processes transpire that take time and eventually result in movement of the intended effector. Timing of responses may become more variable if motor implementation is affected by brain damage even though the clock itself may be intact. Thus, increased timing variability following cerebellar insult may be due to either an impaired clock or impaired motor implementation.

Wing (1980) and Wing and Kristofferson (1973) have developed an experimental paradigm and a statistical method for separating the two sources of timing variance. Subjects synchronize tapping (e.g., with the finger) with a pace signal, often a tone, that occurs periodically (e.g., every 400 msec). After some synchronization taps, the tone is turned off and subjects continue to tap for a period, trying to maintain the target interval. From the continuation phase following tone offset, the variance of the inter-tap intervals is determined, and that constitutes the measure of timing precision. By the theory, , where is the clock variance and is the motor variance. In words, total variance in the timing of taps is a compound of variation in the clock generated intervals and variation in the duration of motor implementation following a signal from the clock.

Wing and Kristofferson proposed a way to measure motor variance. Once it and total variance are measured, clock variance can be indirectly estimated by subtracting motor variance from total variance in accordance with the formula above. Here the intuitive basis for their procedure of determining motor variance is presented; formal development of the method is developed in the Wing and Kristofferson references.

Insert Figure 1 about here

Consider three successive timed taps. Each response is initiated by the hypothetical clock. In figure 1 the interval between clock ticks 1 and 2 is called C1, and the interval between ticks 2 and 3 is called C2. Over a long string of such clock

ticks, corresponds to the variance of the intervals Cj. When the clock ticks, it starts a chain of motor processes that take time and eventually results in a response at some time lag after the clock initiation. That time lag is called motor delay and, like the clock intervals, it too is assumed to vary randomly in its duration from tap to tap, having a variance of . If it is further assumed that successive clock intervals and successive motor delays, though variable, are all uncorrelated, then the total variance is the sum of the clock variance plus twice the motor delay variance (two times the motor delay variance is what we had earlier called motor variance). Now, suppose that motor delay is by random chance longer than normal on a single tap as in the middle tap of the middle panel of figure 1. The result will be to lengthen the preceding intertap interval and simultaneously shorten the following interval. On the other hand, if motor delay on a particular tap is short by chance (bottom panel of figure 1), that will tend to shorten the preceding interval and lengthen the following one. Thus, the model predicts that because of random variation in motor delay, successive intervals will negatively covary in their length--i.e., there will be a tendency for long and short alternation in interval lengths. Note that this prediction depends on the assumption that a following clock interval is not adjusted according to the magnitude of the previous motor delay. Motor delays and clock intervals are assummed to be independent.

If the motor delay did not vary, then there would be no negative covariance of successive intervals; the intertap intervals would vary but successive ones would not be correlated. What this turns out to mean is that the magnitude of the negative covariance of successive intervals is an estimator of the motor delay variance.

Let us summarize the basic idea. If a clock is disturbed that will manifest itself in an inflated variance of intertap intervals, but it should not influence the covariance of successive intervals. If motor implementation is disturbed, making motor delay more variable, that will manifest itself in two ways, increased variance of intervals and increased covariance of successive intervals (an increased tendency for short and long alternation). Once the motor delay variance is estimated from the covariance of successive intervals, the clock variance can be estimated by subtracting twice the motor delay variance from the total variance (i.e.,)

To apply the model to the analysis of patients, one must have some confidence in its validity. A review of various predictions of the model and their confirmation is given in Wing (1980, c.f., also Vorberg & Hambuch, 1984, for extensions of the model to bilateral tapping). To provide some idea of the nature of the predictions, however, it was noted that this clock model predicts a negative covariance of successive intervals. A different model of timing, a feedback model (Wing, 1977a), does not make such a prediction. Since negative covariance is found for virtually all subjects, the clock model is supported. Second, the clock model predicts that the longer the intervals being timed the larger the clock variance. Motor delay variance, however, should be unaffected by the length of the interval being timed, since motor delay is just implementation time. These basic predictions have been confirmed. A feedback timing model suggests that if receipt of feedback from a response is delayed or advanced, then the next interval will tend to be delayed or advanced by the same amount. Wing (1977a) has shown this not to be the case for auditory feedback from each tap for humans, and

Conrad and Brooks (1974) have shown it not to be the case for proprioceptive changes in feedback in monkeys. This failure of a feedback based theory of timing supports the alternative clock model. Thus, a considerable body of evidence favors the clock model as outlined.

Our larger goal is to apply the Wing methodology to a variety of patients who have timing difficulties. We wish to determine those portions of the brain that affect timing via a clock and those portions that influence timing via motor delay. Such functional separation of the two contributors to motor variance would not only reveal properties of different brain systems, but would give added validity to a timing model that postulates a clock as separable from motor implementation.

Wing, Keele, and Margolin (1984) describe a Parkinson patient with large lateral differences in symptoms, allowing a comparison of one hand with the other. In addition, over the course of a year the disease progressed considerably, but the progressive deterioration was confined largely to the more affected right side. This patient showed neither differences in motor delay variance between the limbs nor changes in motor delay variance over the course of the year. The patient did show an initially impaired clock component in the right hand and it further deteriorated over the year.. This result implicates the basal ganglia as part of a clock system. In contrast, a preliminary report of a patient with peripheral nerve damage in the arms appears to show inflated motor variability (Ivry & Keele, 1985).

In this study we report on a unilateral cerebellar patient. Such a patient allows a comparison of clock and motor delay functions between right and left hands. In addition, we administered a perceptual timing task in which the patient judged the relative durations of successive auditory based time intervals. That task, while being analytic to timing, doesn't lend itself to left versus right comparison as is the case with motor production. We have, however, used the same task on a group of normal subjects allowing some comparison with the patient.

Methods

Patient

The patient at the time of testing in the spring of 1984 was 44 years old. She was left handed prior to cerebellar damage. In 1979 she underwent a craniotomy to remove a hemangioblastoma limited solely to the left cerebellar hemisphere. Due to post-operative swelling and hydrocephalus, she required subsequent placement of a shunt. She recovered from surgery without intellectual impairment. However, she had been left with some mild slurring of her speech, problems with balance, and loss of dexterity in her left hand which have not permitted her to return to regular employment as a typist.

The visual fields and cranial nerves were intact. The extraocular movements were full and there was no nystagmus. Her saccades were hypermetric, especially on gaze to the left. Examination of motor function in the upper extremities revealed normal strength. There was perhaps slight hypotonia in the left upper extremity with spooning of the left hand and wrist. Check reflexes were intact in both upper extremities. When

the arms were extended in front of her and tapped gently by the examiner, there was more "bounce" in the left upper extremity. Finger dexterity was less in the left hand than in the right. Sequential tasks such as rapid tapping movements with the hand and pronation-supination were a bit slow and clumsy on the left. Finger-nose-finger was performed without past pointing and accurately with some mild end-point dysmetria but no gross ataxia. In the lower extremity, toe tapping was less regular and clumsy with the left foot than the right. There was no dysmetria and heel-shin testing was performed normally with both lower extremities. The deep tendon reflexes were normal and symmetric except for decreased ankle reflexes bilaterally. The plantar responses were flexor bilaterally.

The patient had no difficulty arising from a chair and did not lose her balance when bending over to pick things up off the floor. Her gait was normal except for a slight widening of the base and a tendency to be off balance at times. Her pace and stride were normal. She was unable to run. She could stand on either foot but could not hop on her left foot. Romberg sign was negative. Postural righting reflexes on gentle perturbation were intact. She was able to perform tandem walking with some difficulty.

The overall impression is one of mild residual cerebellar syndrome. The mild impairment leaves both hands functional and allows their comparison.

Comparison Subjects

Although we are primarily interested in comparison of left and right hand performance of the patient, for some purposes we wished to compare her performance to a normal population. At an earlier point in time a sample of 15 neurologically normal older subjects aged 62-73 were run on the same motor timing task. In addition, in the context of another study (Keele, Pokorny, Corcos, and Ivry, 1985) we ran a sample of 32 younger normal subjects aged 18-35 years on the same perceptual timing task as for the patient.

Tasks and Procedure

In the tapping task the patient rested her palm on one metal plate and tapped another metal plate with her extended index finger. Tapping the second metal plate closed an electrical circuit. In each trial bout the first finger movement initiated a series of 20 pace tones that came from a speaker. On some bouts the tone occurred every 450 msec and on other bouts it occurred every 550 msec. The subject attempted to synchronize tapping with the tone, one tap per tone. After the 20th tone the pace signal stopped, but the patient continued to tap an additional 30 times attempting to maintain the same interval as defined by the pace tone. All the measures of interest come from the inter-tap intervals following offest of the pace tone during which timing is internally generated.

The patient was run in one practice and 6 additional sessions, each lasting 1 to 2 hours. During each session there was an attempt to obtain 6 good tapping bouts of 30 continuation taps for each hand at each intertap target interval. If the patient failed to make contact with the touch plate, noticeably paused, or slightly tremored, the

variance on that bout would be greatly inflated and not representative of most of the performance. An additional bout was run to increase the useful data sample whenever an unusually high variance was observed, but data from abberant bouts were retained for confirmatory analysis.

The 15 normal older subjects each received two similar sessions of testing with the only notable change that they tapped a microswitch button rather than a metal plate. We have not noticed any marked differences in scores between the touch plate and the microswitch apparatus, but the different apparatus calls for some caution in comparisons of the patient with the controls. The data from these subjects had been collected sometime prior to studying the patient. Although the control subjects are considerably older than this patient, their performance presumably sets a lower bound on that of normal people.

On four sessions the patient was also run on a perceptually based time judgement task. The subject heard two successive pairs of clicks and judged whether the interval between the members of the second pair was less than or greater than that of the interval between members of the first pair. The first interval was always 400 msec. An adaptive procedure was used based on 120 judgements per session to calculate an upper and a lower threshold. The upper threshold was a value that would be judged to be longer than the standard about 70% of the time; the lower threshold was a value that would be judged shorter than the standard about 70% of the time (footnote 2). The procedure is described in greater detail in Pentland (1980), Liberman and Pentland (1982) and Pokorny (1985).

The same perceptually based time judgement task had been conducted with 32 younger subjects in the context on an earlier study (Keele, Pokorny, Corcos, and Ivry, 1985).

Results

Production Timing

If a subject pauses, fails to touch the plate on a movement, or tremors, unusually long or short inter-tap intervals will greatly inflate the inter-tap variance. Such was occasionally the case with this patient, and whenever it occurred, the bout was replaced. Such replacement occurred most frequently with the left hand. Even with this selection, some tapping bouts produced uncharacterisically large variances from changes in tempo and intensity due to an obviously awkward movement, and again such aberrant trials were more frequent for the left hand. As a result, the following analyses were based on the best four tapping bouts per session for each hand at each interval. This procedure is conservative in that it compares the hands on the best performance of which they are capable, and the left hand still exhibits a deficit compared to the right hand, even though selection favored the left. The basic results are virtually identical in pattern to those from an alternate method (not reported here) in which all tapping bouts are analyzed but with aberrant i n t e r v a l s dropped from individual bouts, and the analysis is based only on the remaining intervals.

The variation in intertap intervals following the offset of the pace tone is analyzed using the autocovariance of lags 0 through 5. The lag 0 autocovariance is the

same as the variance of the intertap intervals. The lag 1 autocovariance describes the relation between immediately adjacent intervals. If the lag 1 autocovariance is divided by the lag 0 autocovariance, the measure is the same as the correlation between successive intervals. In Wing's (1977b, 1980) basic model, the lag 1 autocovariance should be negative in sign, indicating a tendency for short intervals to be followed by long ones and the reverse. The square root of minus the lag 1 autocovariance estimates the standard deviation of the motor delay. A lag 2 autocovariance measure involves the relation between intervals separated by one intervening interval, lag 3 refers to the relation of intervals separated by two other intervals, and so on.

In the basic model, if it is assumed that both successive clock intervals and successive motor delays are independent random variables, then all autocovariances at lags greater than 1 should be 0 in value except for random error in their estimates. Table 1 shows the autocovariances for the cerebellar patient for lags 0 through 5. As predicted, lag 1 is negative. However, the covariances at larger lags differ considerably from 0.

Insert Table 1 about here

Because of non-zero covariances at lags greater than 1, we have analyzed the data in two ways. The first way takes no account of the autocovariances at longer lags. Motor delay variance is estimated from the lag 1 autocovariance, and clock variance is estimated by subtracting twice the motor delay variance from the total variance of the inter-tap intervals. These uncorrected estimates of clock and motor variance, along with total variance, are shown in Table 2. In general they show a large increase in clock variance for the left hand. However, the motor delay variance on the right hand at the fast tapping rate is unexpectedly large, raising suspicion with the small clock value for the right hand at that rate. First, the Wing model predicts that an upper bound for motor delay variance is half the total variance. With a larger motor variance, clock variance would become negative, since clock variance is total variance minus twice the motor delay variance. Negative variance is of course impossible. Thus, the fact that motor delay variance in the fast, right hand condition is so large relative to total variance suggests that assumptions of the model have been violated. Second, the large lag 2 autocovariance in the fast, right hand condition further suggests violations of th basic model assumptions.

Insert Table 2 about here

The second analysis corrects the estimate of clock and motor delay variance taking into account the non-zero covariances at large lags. This is done using an iterative curve fitting procedure that assumes one of four types of dependency (Wing, 1977b): (1) correlations between successive clock intervals, (2) correlations between successive noise values that affect clock intervals, (3) correlations between successive motor delays, and (4) correlations between successive noise values that affect motor delays. These are referred to in Wing (1977b) as models I, II, III, and IV.

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Insert Table 3 about here

Table 3 shows corrected values of clock and motor delay variance based on the best two fitting models. For the right hand at the 450 msec target interval, model I provided the best fit, but model III was almost as good. For the left hand at the 450 msec. target interval, model IV provided, the best fit, but model III was again about as good, though with opposite correlational sign to that for the right hand. It is clear that these models yield substantially different conclusions at the fast tapping rate than do the uncorrected estimates of clock and motor delay variances. If model III is assumed, there still remains a larger clock variance in the left hand, but if the slightly better fitting models are assumed, there is little difference between left and right hands in either clock or motor delay variances. The fast tapping rate appears, therefore, to induce sequential effects in the inter-tap intervals that obscure the basic question.

At the slower rate, however, such sequential effects are less prominent and the picture remains clearer. For the right hand tapping at the 550 msec. target interval, no model provides a superior fit to the basic model. Thus, clock and motor delay variance estimates are unaltered. For the left hand, there is little difference in the fits of the different models, including the basic model. Neither model III nor the slightly better fitting model IV alters the clock and motor delay variance estimates to an appreciable degree. Therefore, it appears justified to statistically compare the uncorrected scores of left and right hands at the slower 550 msec pace where problems of covariances at large lags are less prominent.

The patient performed in 6 experimental sessions with each hand at the 550 msec target interval. A t test comparing the means over the 6 sessions showed a significant difference ($p < .01$) on total variability, ($t = 4.22$, 5 df). For the component variances of clock and motor delay, only clock variability showed a significant difference ($p < .01$) between hands, ($t = 4.41$, 5 df).

Insert Table 4 about here

It is of interest to compare the clock and motor delay variabilities in this cerebellar patient to the mean of the 15 older subjects. Table 4 shows the relevant data. Recall that the data for the cerebellar patient were selected by leaving out the worst bouts of performance. The data for the older subjects was unselected. Although all the older subjects were right handed, there is little asymmetry between their left and right hands. This suggests that the asymmetry in the patient is due to brain damage and not handedness. Compared to the mean of the older population, the cerebellar patient has an inflated clock variability on the left hand at the slower rate. Only 2 of the older subjects had as high clock variability on either hand as the cerebellar patient's left hand. The cerebellar patient's clock variance on the left hand at a 550 msec. target interval was 1.36 standard deviations above the mean of the older control subjects.

To summarize the tapping data, the cerebellar patient has high clock variability on the left hand, at least at slower speeds, and relatively normal clock variability on the right hand. Motor delay variabilities are in the normal range.

Perceptual Timing

On the perceptual task upper and lower thresholds were calculated as measures of the patient's ability to differentiate durations that differed from a standard 400 msec duration. The difference is a measure of temporal acuity of perception of duration. The difference for each of the four sessions was 96, 72, 64, and 64, and averaged over the 4 sessions the difference is 74 msec. For 32 younger normal subjects the mean difference between upper and lower threshold averaged 36, a range half that of the cerebellar patient. Of the 32 normal subjects, only one had a range as large as that of the patient and that range was 79 msec. The next two largest ranges in the normal population were 63 and 57 msec.

Discussion

An earlier study using the same methods as the present one (Wing, Keele, and Margolin, 1984) found evidence of a clock disorder localized to one side of the body in a Parkinson patient. That evidence suggests that some portion of the basal ganglia is involved in timekeeping. In this study a left cerebellar patient had an elevated timing variance in motor production on the left hand. Decomposition of the variance suggests an inflated clock variance on that hand. Moreover, there is a hint that the cerebellar patient may also show a perceptual deficit in the judgement of perceptual durations. Thus, both cerebellar and basal ganglia functions appear implicated as components of a clock system.

At this point, prior to the following speculations, caution regarding conclusions must be raised. This cerebellar patient shows complex sequential dependencies among successive intervals at fast rates of tapping that make difficult the application of the Wing and Kristofferson model. Application of more sophisticated models to account for the sequential dependencies left ambiguous results. The resultant selectivity of data requires investigation in other subjects. Also, the sequential dependencies raise the possiblity that some kind of tremor is imposed on the basic temporal structure. We do not at this time understand how tremors would affect the Wing and Kristofferson model. On the perceptual task we also lack competely satisfactory controls, as the patient cannot serve as her own control in that case. Thus, the following remarks are speculative, serving primarily to stimulate further investigation of neural organization in relation to timing.

It is common to think of a clock as a pacemaker system localized in one part of the brain. The suggestion that a clock disorder arises from two different sections of the brain suggests that it might be preferable instead to think of the timing system as a circuit that passes through several brain subsystems. Figure 2 provides a framework for speculation about this issue. The cerebral cortex sends direct commands to the musculature through the pyramidal tract to interneurons and motor neurons in the spinal

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cord. In addition, the cortex sends efferent messages to both the cerebellum and the basal ganglia, and in turn the cortex receives back input from those two systems through the thalamus (c.f., Ghez, 1981 and Pansky, 1980). One might speculate that the "clock" consists of the circuit from cortex to cerebellum and basal ganglia and back to motor cortex and that motor implementation via the pyramidal system follows receipt of the message back to the cortex from cerebellum and basal ganglia.

Insert Figure 2 about here

Using this basic framework, one might suppose that executing timed responses occurs in this fashion: The cortex triggers a response via the pyramidal system. The transmission time corresponds to what we have labeled motor delay. At the same time as the issuance of a response, the cortex may call for a next response at a target time. The time delay is determined by the latency of an internal loop through cerebellum and basal ganglia and back to the cortex. Noise could be added not only by cerebellar and basal ganglia damage but at other places in the loop as well, such as in the motor cortex or thalamus. This framework suggests patient types that might, therefore, exhibit a clock disorder. Since variance in the loop time constitutes clock variance, any place in the loop that imposes noise will add to the clock variance. Neither the initiation of the next response nor the initiation of the next clock cycle occurs until the return message to the cortex is complete. It is in this sense that the clock system may not best be characterized as a pacemaker system with periodic bursting but rather as a system that processes a request for a next response only after a preceding one is issued. This conception is similar to a feedback model but one in which the feedback is central rather than peripheral from the kinesthetic sense organs of the moving effector.

Within this framework, the issuance of a response and the triggering of the next cycle may depend on complete programming of a response. One portion of the brain may be primarily responsible for adjusting the duration of the cycle time. Conceivably the cerebellum contains that mechanism. Before the next cycle of time is started, other parameters of the motor program, such as force, might have to be set (c.f., Keele, 1981, 1985 for a discussion of evidence regarding pre-programming of parameters and Ivry, 1985, for a study of force programming). The basal ganglia might set the force. If that process is impaired, it too would add to the variance prior to initiating the implementation of response via the pyramidal system, because implementation cannot begin until all parameters are finalized. Since variation in the release of a response would also produce variation in the loop time, the impairment would manifest itself as increased clock variance rather than motor delay variance.

In this scenario, it is supposed that although both cerebellar and basal ganglia contribute to clock variance, the two mechanisms serve different functions in the clock cycle, the cerebellum metering out time and the basal ganglia regulating force. Conceivably the reverse could be the case, or some other brain component of the timing loop might be the source of time metering. A variety of evidence does suggest, however, that Parkinson patients, who have basal ganglia damage, do have impaired force control. The patient studied by Wing, Keele, and Margolin (1984) was bradykinetic in one hand, as

shown by slowness in covering the distance necessary to arrive in the proximity of a target. Informal observation gave the appearance of very weak movement in tapping with the impaired hand. Hallet and Khoshbin (1980) found bradykinetic patients to exhibit multiple electromyographic bursts in producing flexion movements. Since normal subjects show only a single agonist-antagonist cycle (or sometimes agonist-antagonist-agonist), it appears that the initial burst of bradykinetic patients is impaired in force. Other Parkinson patients may show marked rigidity, and that might be another type of force malfunction. Finally, Margolin and Wing (1983), in an analysis of handwriting of Parkinson patients, found that when patients are low on medication, force of movement trails off during the course of writing, manifesting itself as a combination of slowing and reduced amplitude. Thus, it makes sense as a working hypothesis to suggest that the basal ganglia system affects clock timing only in that damage to some portions makes variable the setting of a force parameter prior to completing a timing cycle and initiating the next response.

Although the present study suggests that a cerebellar patient has impaired perceptual timing, we know of no evidence at present that the cerebellum houses the expandable portion of the timing loop. Nevertheless, such an assumption may form a useful working hypothesis to stimulate further investigation. The present research best defines an issue rather than provides a definitive answer.

The view of a clock as a loop involving several brain systems makes more understandable why clock variance may sometimes exhibit a unilateral increase, as in the case with the cerebellar patient of the present study and the Parkinson patient of the Wing, Keele, and Margolin (1984) study. At least portions of the loop from cortex to cerebellum and basal ganglia and back to cortex would be lateralized, and damage along the loop would show up as unilateral clock impairment.

Further comment is needed concerning whether or not the cerebellum participates in the timing of perceptual events. Some brain structure must participate in both motor and perceptual timing. For example, if you hear two tones separated by a brief interval, you can then produce that interval with two taps. The perceptual time judgement has been translated into a produced time interval. Moreover, in our other work (Keele, Pokorny, Corcos and Ivry, 1985) we have found that the degree of variability in inter-tap intervals correlates across individuals with the acuity of perceptual judgements--i.e., people with large inter-tap variance also tend to have poor acuity in judging the durations of perceptually defined time intervals. Such results suggest a timing mechanism in common to perception and production. Although the data of this study suggest impaired perceptual time judgements in a cerebellar patient, this suggestion must be viewed cautiously. There is no within patient control for the perceptual judgements as there is for motor production where one hand serves as a control for the other. Although, the patient has poorer perceputally based time acuity than all but one of 32 normal subjects whom we have tested on the same task, the normal subjects are younger by 10-25 years. Possibly perceptual time judgement is an ability that changes rapidly even by the mid-40s, but we have no relevant evidence. At best, therefore, the initial investigation of non-motor timing in this patient serves to alert one to the possibility that the cerebellum may be part of a general timing mechanism.

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It is the case that the cerebellum receives both auditory and visual inputs via the temporal, occipital, and parietal lobes (Pansky, 1980). There is a paucity of hypotheses for the cerebellum's operations on these inputs. Timing is a plausible operation.

Footnotes

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2. The thresholds are plus and minus one standard deviation from the point of subjective equality assuming a logit distribution.

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Table 1
Autocovariance of Tapping Intervals for Patient JB

Interval	Hand	Lag 0	Lag 1	Lag 2	Lag 3	Lag 4	Lag 5
450 msec	right	1299	-632	156	-78	-5	-8
450	left	1244	-256	-127	-14	-24	-48
550	right	1063	-344	-3	-9	12	-14
550	left	1732	-376	-54	-84	57	-106

Table 2

Uncorrected Total, Clock and Motor Delay Variabilities for Cerebellar Patient JB: (Standard Deviations in Msec).

Target Interval	Hand	Mean Interval	Total SD	Clock SD	Motor SD
450 msec	Right		36.0	5.9	25.1
450	Left		35.2	27.1	16.0
550	Right		32.6	19.4	18.5
550	Left		41.6	31.3	19.4

Table 3

Corrected Clock and Motor Delay Variabilities for Cerebellar Patient JB: (Standard Deviations in Msec)

Target Interval	Hand	Model	Clock	Motor Delay	Correction Factor
450 msec	Right	I	21.5	18.4	-.50
		III	15.9	20.3	-.21
450	Left	IV	22.0	21.7	.26
		III	20.6	23.8	.38
550	Right	All models	19.4	18.5	.00
550	Left	IV	30.0	20.4	.09
		III	30.7	20.4	.05

Note: the correction factor indicates how much the preceding clock or motor delay interval or noise is weighted in determining the current interval (c.f., Wing, 1977b).

Table 4
Clock and Motor Delay Variabilities for Cerebellar Patient and 15 Control Subjects Aged 62-73 Years: (Standard Deviations in Msec)

		Right Hand		Left Hand	
		450	550	450	550
Cerebellar Patient (corrected values)	Clock	21	19	22	30
	Motor Delay	18	19	22	21
Controls (uncorrected values)	Clock				
	Mean	16	21	14	22
	SD	10.6	8.3	8.3	5.9
	Motor Delay				
	Mean	17	17	19	17
	SD	6.2	6.7	5.8	6.4

Note: For 15 control subjects, mean refers to clock and motor delay variabilites averaged over subjects, and SD refers to standard deviations of the clock and motor delay variabilities across subjects.

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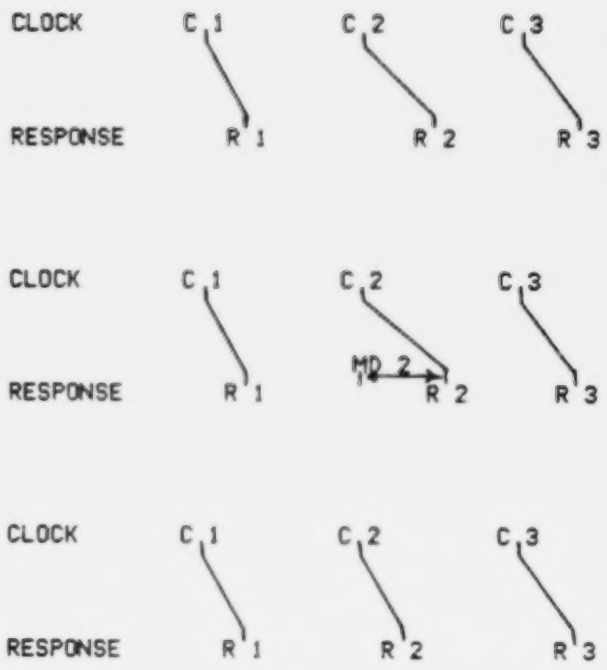

Figure 1: An illustration of the clock model of Wing and Kristofferson (1973). In panel 1, an internal clock is assumed to generate clock ticks, C1, C2, C3, etc. The variance of the intervals is . Each clock tick initiates motor processes that after some delay, MD, results in a response, R. A particular clock interval is independent of whatever motor delay preceded it. The middle panel shows that if MD2, the motor delay following C2, is by chance large, the preceding interval will be lengthened and the following one shortened as compared to panel 1 in which everything is the same except MD2. The bottom panel shows that if MD2 is short by chance, then compared to the top panel, where again everything except MD2 is the same, the first interval is shortened and the following one lengthened. Thus, the clock model predicts a negative correlation between the lengths of successive intervals. This figure is adapted from a similar conception by Wing (1980).

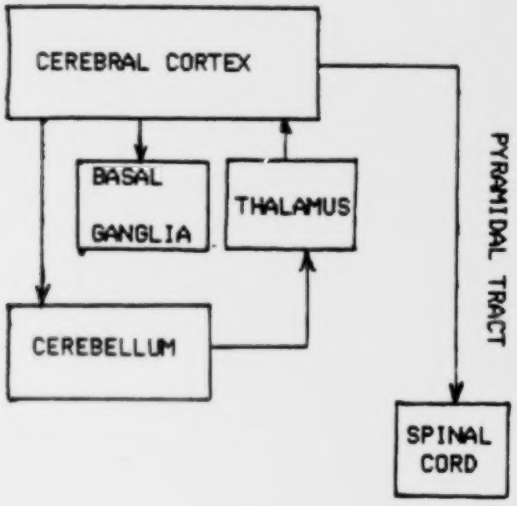

Figure 2: A schematic diagram showing a loop from the cortex through the cerebellum and basal ganglia and back to the cortex. This loop represents clock time with variance σ_c^2. The output from the cortex through the pyramidal tract and the spinal cord to the effector represents motor delay with variance σ_{MD}^2.

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